

COMPARISON OF SEVERAL METHODS FOR REAL PEDESTRIAN ACCIDENT RECONSTRUCTION

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ABSTRACT

The aim of this paper is to evaluate and compare several methods allowing the reconstruction of real accidents involving pedestrians. These different methods have various levels of complications and are commonly used in primary or secondary safety research. They can be classified into three categories corresponding to their levels of complications. The first class concerns "simple" methodologies based on an analytical or semi-analytical approach ("hand-calculi") such as Searle's model, Fall and Slide model, equations proposed by Rau et al., Simms et al., etc. The second one is more complicated and considers for example the pedestrian as a single segment as described by Wood. Finally, the last class contains the most complicated approaches and is based on three-dimensional multi-body models. Concerning this third class, this work has been based on the PC-Crash® and Madymo® softwares. We have tested all of these methods for one of the most usual real car-to-pedestrian accident configurations: frontal collision with pedestrian wrap trajectory. Data issuing from two real cases have been used. They have been provided by an in-depth multidisciplinary accident investigation (psychology, technical, medical). Reconstructions are thus based on driver and witness statements, on accurate information relating to material evidence (e.g. skid marks, car damage, pedestrian injuries, throw distance) and parameters fitted to vehicle and pedestrian (e.g. vehicle shape, pedestrian anthropometry, etc). Results have been compared in terms of quality of the reconstruction balanced by the limitation of the different methods. Evaluated elements are in particular the speed of the vehicle, the final position of the pedestrian, his kinematics, the impact points on the car and injuries (when the method allowed it).

In parallel, methodologies have also been compared qualitatively by establishing the necessary means to apply them. In this way, the potentiality of the methods, their requirements (necessary input data, into operation bringing time, computer time) have been evaluated and reported in a general matrix. It allows us to summarize advantages and disadvantages of the different methods.

INTRODUCTION

Several sorts of methods are commonly used to reconstruct a real car-to-pedestrian accident. All of them are based on a "model" which is the abstract simplified representation of the reality. These models are uncompleted and temporary results of the building up of knowledge, which we have from a reality. In agreement with this status, the models can be more or less complicated according to modelling assumptions. Level of complication is so dependant on the mathematical hypothetic-deductive system, the input and output data definition, coherence of the concepts taking into account the modelling, etc.

We took an interest in comparing some different dynamic hypothetic-deductive models (more precisely, some models of Newtonian Mechanics) used to represent a real car-to-pedestrian collision in the most usual configuration, i.e. a vehicle frontal impact with a pedestrian wrap trajectory. These models are based on the Galilean-Cartesian paradigm which does not take into account the complexity but the complication. It was therefore interesting to observe if they can propose a collision reconstruction (impact and post-impact phases) fitted to the reality, even if they split up this complex event (a priori irreducible) into simple problems which have to be treated one by one. It was relevant to determine in what propor-

tion the increase in complication of a model, as used in a secondary safety research way, can improve the findings of the forensic and the in-depth investigation fields.

Chosen models have been classified into three categories as regards their complication level:

- a first category concerning simple methodologies based on an analytical or semi-analytical approaches (hand calculi): Searle's model [13], Fall and slide model [4], equations proposed by Rau et al. [11], Toor and Araszewski [17], Simms et al. [15],
- a second one illustrated by the Wood's Single Segment Method [18] in which the pedestrian is considered as a single two-dimensional solid (a segment),
- a third one containing the most complicated approaches based on three-dimensional multi-body models of the pedestrian (used with PC-Crash® [9, 10] or Madymo® softwares).

Data issuing from two real and well-documented (by an in-depth multidisciplinary investigation) cases have been used to test these different models. The objective consists in evaluating their potentiality and their requirements in terms of input, output, time consumption, etc.

Beyond this comparison, this study provided the opportunity for fruitful, scientific and methodological exchanges between connected ways which work towards improving the road safety policy with prevention or repression (from a forensic point of view) finalities:

- in-depth multidisciplinary investigation field [5]: it is mainly orientated towards primary safety and belongs to the research field with a clinical thought process. Based on the complexity paradigm, it studies the dysfunctions of the Human-Vehicle-Environment system and also interactions between its components, from several points of view: psychology, automotive mechanics, theoretical mechanics, road infrastructure, medicine,
- biomechanics applied to the vehicle passive safety research: it tries to understand, by experimental (for example with Post Mortem Human Subject - PMHS - tests) and theoretical approaches, the relations between vehicle design and human injury mechanism (e.g. to establish the influence of front bumper design on pedestrian lower leg injuries),

- forensic kinematic road accident reconstruction work: its aim is to provide the judicial court evidence relating to the crash sequence, the collision configuration, the impact configurations and the respective behaviour and velocity of vehicles involved for each sequence.

IN-DEPTH ACCIDENT INVESTIGATION

With regard to real data, two cases of car-to-pedestrian collision with wrap pedestrian post-impact trajectory were selected. They issue from the in-depth investigation database of a research unit (department of Accident Mechanism) belonging to the French National Institute for Transport and Safety Research (INRETS), which has been carrying out multidisciplinary studies on road accident since the beginning of the 80's [6]. In these two cases the "point" of impact and the rest position of the pedestrian were known on the accident scene.

In the first one, some skid marks are related to the front track of the accident-involved vehicle. These tyre marks, the collision configuration, the final configuration and the "point" of impact classified this case as a typical pedestrian wrap trajectory as was defined by Ravani et al [12]. Moreover, the tyre marks allow to determine the vehicle impact velocity by an alternative way expressing the kinetic energy loss as a function of the length of the marks and a mean given deceleration.

In the second one, no material evidence was related to the vehicle behaviour (deceleration beginning unknown) even if this vehicle is not equipped with an Antilock Braking System (ABS) system. This case corresponds to a pedestrian wrap trajectory regarding the vehicle-pedestrian contact sub-phase, but it is not typical (cf. relative rest position of vehicle and pedestrian). It represents a configuration in which (without a vehicle Event Data Recorder or reference crash tests) the modelling of the pedestrian impact and post-impact trajectory seems to be the only solution to determine the vehicle impact velocity.

- case No 1:

A January day, at 9 a.m., the weather is dry and sunny. A Citroën Xantia® vehicle was driving along a boulevard in urban areas. In the middle of its lane, the vehicle crashed into the right side of an old man on a pedestrian crossing. It braked in emergency before impact. The pedestrian died on the spot (see figure 1).

- case No 2:

A June day, about 8 a.m., the weather is dry and sunny. A Renault Twingo® vehicle was

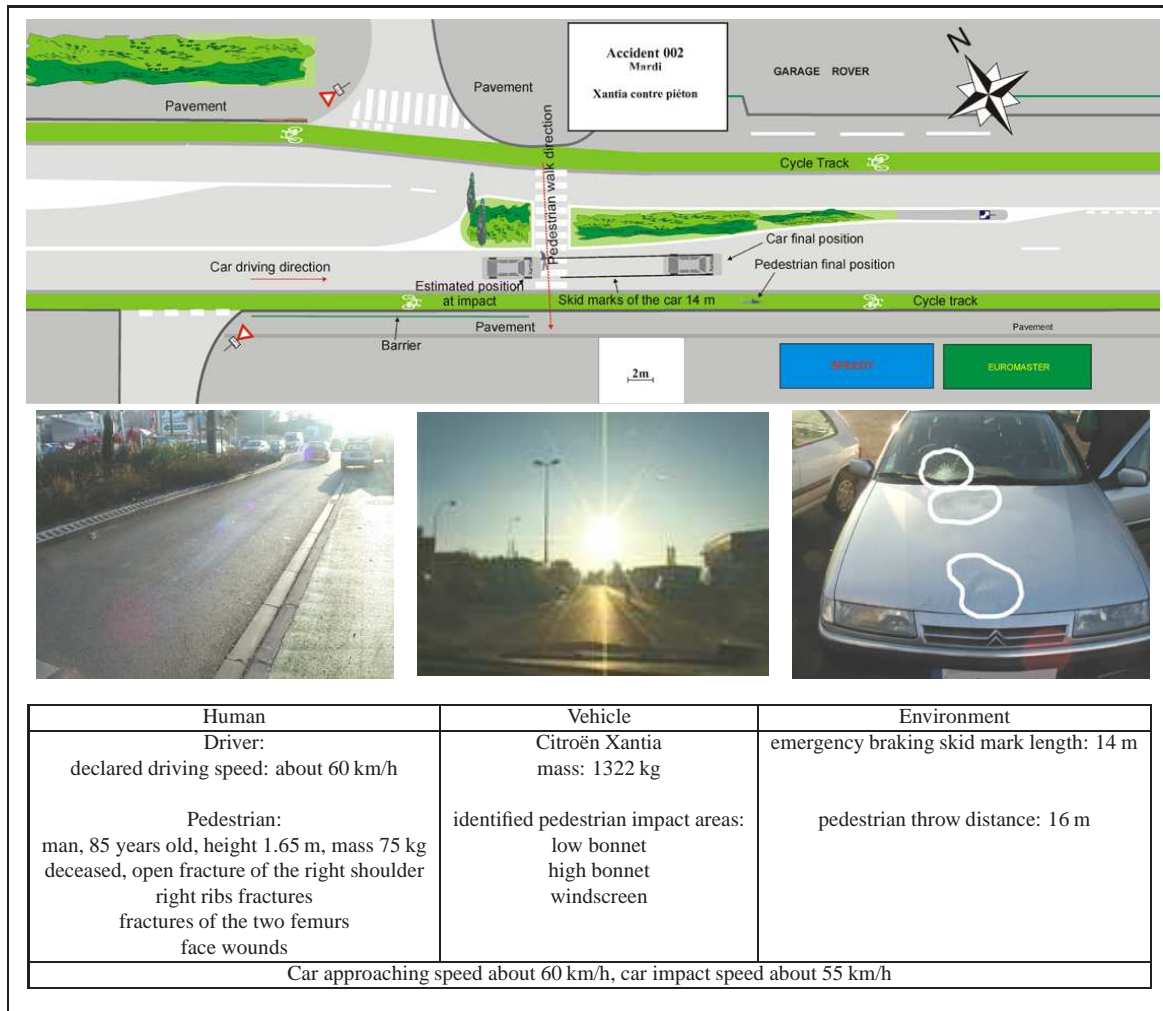


Figure 1. Case No 1 (some in-depth investigation data).

driving through a village. It crashed into the left side of an old woman on a pedestrian crossing. She died as the result of her injuries the next day. The vehicle driver was a priori dazzled by the sunlight. He did not see the pedestrian and didn't begin to brake before impact (see figure 2).

MODELS

Simple Models

With regard to the first above-mentioned model category, some models with a simple mathematical formalism (even if they are the results of a great amount of research) are considered. They can be classified as analytical or semi-analytical methods. Most of the analytical ones derive from fundamental mechanics equations and correspond to a modelling of a pedestrian post-impact trajectory part: airborne and

ground-pedestrian sub-phases (see figures 3 and 4). They are based on a 2D kinematics applied to the pedestrian centre of gravity. Two usual and well-known models have been chosen: "fall and Slide" [4] and Searle's "fall, bouncing, sliding" model [13] which tries to take into account pedestrian bounces on ground (see figure 4). Their respective mathematical expression (equations 1 and 2) proposes a relation between pedestrian projection speed $V_p(t_p)$, projection angle θ , a partial throw distance $D_2 + D_3$, vertical distance H_2 between projection moment t_p and first contact on ground moment t_g , gravitational acceleration g , and pedestrian friction coefficient on ground μ_p .

$$D_2 + D_3 = V_p(t_p) \sqrt{\frac{2H_2}{g}} + \frac{V_p^2(t_p)}{2\mu_p g} \quad (1)$$

$$V_p(t_v) = \frac{\sqrt{2\mu_p g [(D_2 + D_3) - \mu_p H_2]}}{\cos(\theta) + \mu_p \sin(\theta)} \quad (2)$$



Figure 2. Case No 2 (some in-depth investigation data).

The Searle's model allows us to provide a range of predicted pedestrian projection speeds for a given partial throw distance with a mathematical lower bound (equation 3) and an arbitrary upper bound (equation 4).

$$\min\{V_p(t_v)\} = \frac{\sqrt{2\mu_p g [(D_2 + D_3) - \mu_p H_2]}}{\sqrt{1 + \mu_p^2}} \quad (3)$$

$$\max\{V_p(t_v)\} = \sqrt{2\mu_p g [(D_2 + D_3) - \mu_p H_2]} \quad (4)$$

These models are suited for typical wrap trajectories, considering the total throw distance $D_t \approx D_2 + D_3$ and the vehicle impact speed V_0 equal to:

$$V_0 = \frac{1}{PE} V_p(t_p) \quad (5)$$

where PE is defined as an impact factor [4] or a projection efficiency [17]. The use of this factor is rather empirical.

Semi-analytical models can be, on one hand, based on experimental (with dummies and PMHS tests) results or real well-documented collision data. Considered as empirical, they use regression curves between vehicle impact speed and total throw distance without modelling projection processes. On the other hand, they can derive from a statistical approach which is based on a variability study (collision parameters and circumstance factors) and on an analytical study of the three trajectory phases. These statistical models correspond to a mathematical function with a simple formalism, but are result of a great modelling way effort. Both empirical

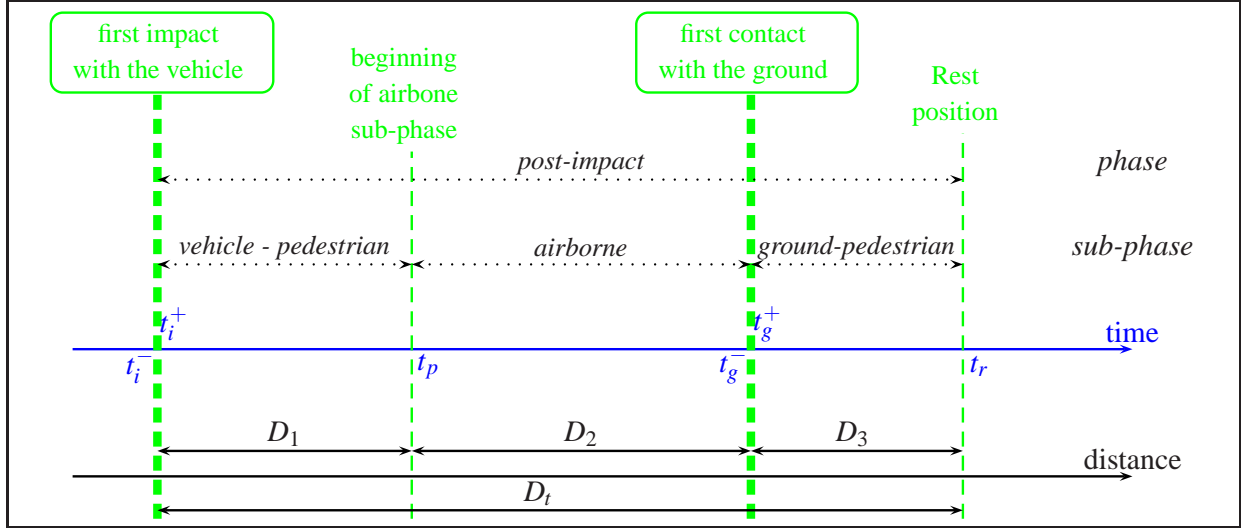


Figure 3. Schematic diagram of impact and post-impact phases corresponding to a wrap trajectory: phases, sub-phases, events, time and distance.

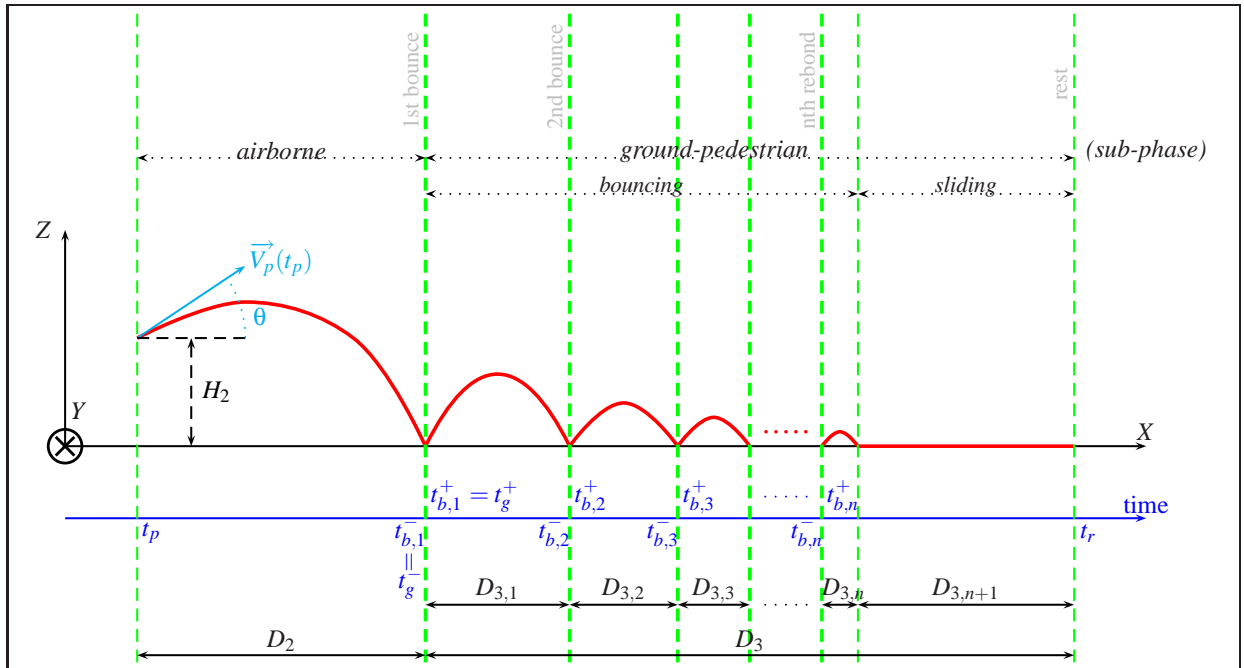


Figure 4. Schema corresponding to the pedestrian centre of gravity trajectory in Searle's model entitled "fall, bouncing and sliding" [13].

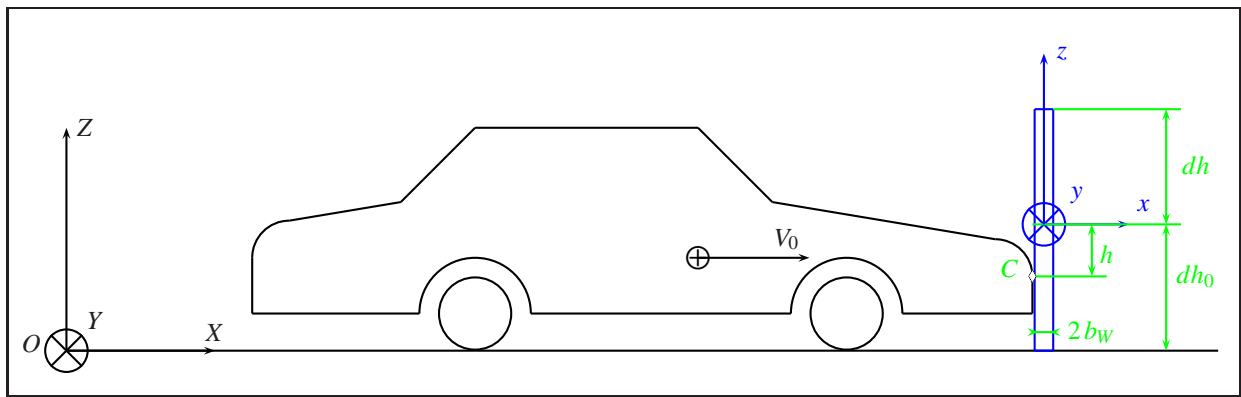


Figure 5. Schematic representation of vehicle and pedestrian segment at primary impact - illustration of some parameters used in Wood's SSM equations.

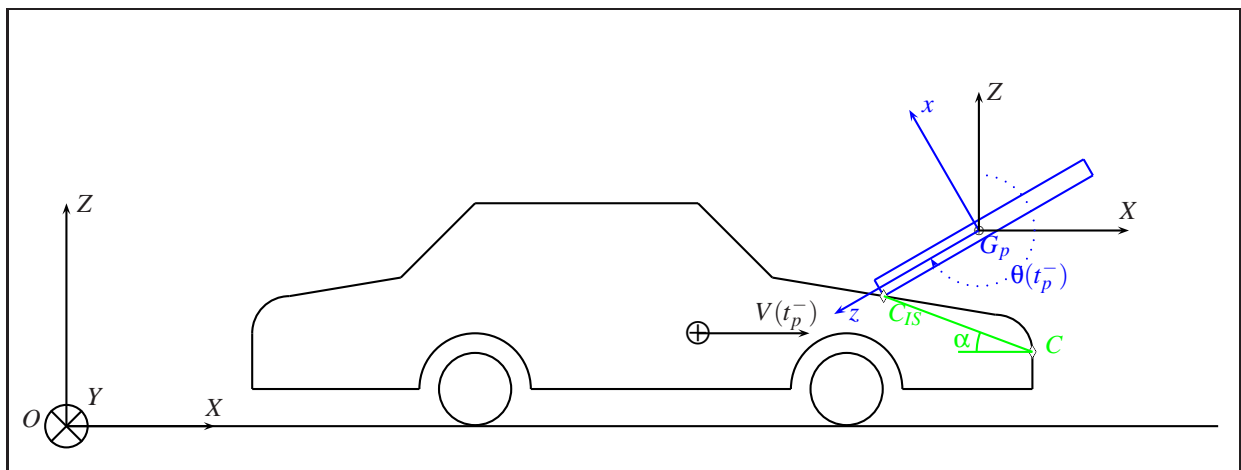


Figure 6. Schematic representation of vehicle and pedestrian segment at secondary impact - illustration of some parameters used in Wood's SSM equations.

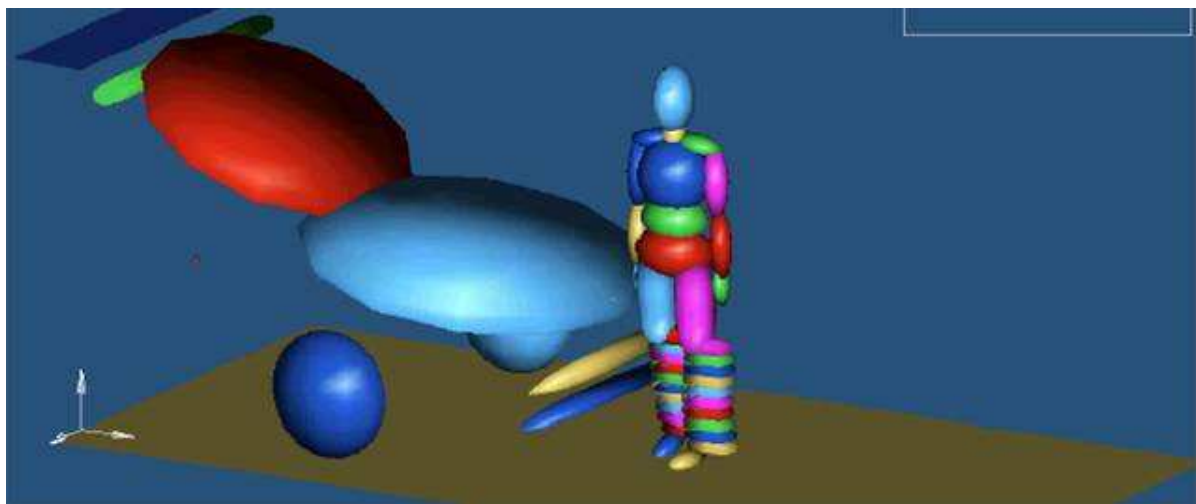


Figure 7. General view of the multibody system (Madymo).

and statistical models enable us to provide a range of value with variable degrees of certainty. Three models have been chosen: two empirical ones (cf. Rau et al. [11], (equation 6), Toor and Araszewski [17], (equation 7)) and a statistical one (cf. Simms et al. [15], (equation 8)):

$$D_t = 0.0052 V_0^2 + 0.0783 V_0 \quad (6)$$

with D_t in m and V_0 calculated in km/h (± 5 km/h).

$$V_0 = 8.25 D_t^{0.61} \quad (7)$$

with D_t in m and V_0 calculated in km/h (± 7.7 km for the 15th and 85th percentile prediction interval).

$$V_0 = \frac{m_v}{m_v + m_p} C [D_t - S_0]^D \quad (8)$$

with D_t in m, V_0 in m/s, and where C , D , S_0 are regression parameters (see [15] to chose a set of regression parameters functions of circumstances and certainty degree in order to determine lower and upper bounds) and m_v (respectively m_p) is vehicle (respectively pedestrian) mass.

Advanced Models

To illustrate the second above-mentioned model category, one model has been chosen: Wood's Single Segment Model (SSM) [18]. It is a mixed analytical formulation (equation 9) for the total post-impact trajectory. It models the vehicle-pedestrian sub-phase considering that the pedestrian could be represented by a single 2D segment (see figures 5 and 6). Then, it models the following sub-phases (airborne and ground-pedestrian) with the Searle's formula considering the pedestrian could be represented by a weighted point. It makes the assumption that there are two vehicle-pedestrian impacts: a primary impact relating to the pedestrian lower part (see figure 5) and a secondary impact relating to the pedestrian head (see figure 6).

$$D_t = \frac{V_p^2(t_p) (\cos(\theta) + \mu_p \sin(\theta))^2}{2\mu_p g} - \frac{k^2 \theta(t_p^-)}{h} + \mu_p (H_2) \quad (9)$$

with k radius of segment gyration and h vertical distance between pedestrian centre of gravity and upper contact point on the vehicle front. $V_p(t_p)\cos(\theta)$, $V_p(t_p)\sin(\theta)$, $\theta(t_p^-)$ and H_2 are functions of vehicle mass, pedestrian segment geometry, secondary impact location, vehicle braking rate, vehicle impact speed V_0 , etc. Segment angle at the beginning of secondary impact, $\theta(t_p^-)$, is more particularly a function of the following parameters:

$$\theta(t_p^-) = f(\theta(t_p^-), V_0, m_v, m_p, \alpha, h, dh, bw, g) \quad (10)$$

with α bonnet angle, dh distance between segment centre of gravity and top (head), bw segment half-width (see figures 5 and 6).

It is worth noting that this model (with a complicated formalism) was the theoretical base of some statistical models (with a simpler formalism) (e.g. Wood's Hybrid Model [19]).

Complicated Models

Concerning the third category which referred to complicated model, two softwares have been used : the PC-Crash V6.0 one and the Madymo V6.0 one. PC-Crash software is a common commercial tool to reconstruct road accidents [3]. A part of this one has been developed to take into account vehicle-pedestrian accidents with a specific pedestrian multibody model and a single body vehicle whose geometry shape is detailed [10]. This approach has been validated with dummy crash-tests and well-documented real cases [9]. The human body model chosen in this paper included 20 bodies interconnected by 19 joints. Default joint and body characteristics fitted to pedestrian mass and height are provided in the software. Eight specific measurements were used to define the front vehicle geometry. Accident configuration was fixed thanks to side pedestrian injuries and vehicle driving direction. The pedestrian position on impact was chosen standing up without speed and with both feet near each other on the ground. The simulation was iteratively used changing impact vehicle velocity and mean vehicle deceleration in order to obtain pedestrian throw distance and impact points on front vehicle measured by the in-depth investigation.

The last method concerns the pedestrian accident reconstruction using a typical multibody software which is commonly used in passive safety. The Madymo software V6.0 has been employed to develop the numerical models and to perform the simulations [16]. The whole multibody model is divided into two parts: the car and the pedestrian (see Figure 7). The human body model has been developed by the University of Chalmers (cf. Yang et al. [21]), Faurecia (cf. Glasson et al. [7]) and validated in collaboration with the Laboratory of Applied Biomechanics (see Cavallero et al. [2]). The original model represents a human body close to the 50th percentile male: 1.75 m, 78 kg. It includes 35 bodies with 35 joints and it is represented by 85 ellipsoids. Joint and body segment characteristics are based mainly on available biomechanical data (cf. Yamada [20] and Kajzer et al. [8]). The specific characteristics of this model concern its lower leg because it is predictive of fractures.

This model has already been validated qualitatively but also quantitatively in pedestrian configuration by comparison with PMHS experimental tests performed at INRETS-LBA (cf. Cavallero et al. [2]).

Concerning the real accident reconstruction, the multibody model was first adapted to the corresponding configuration of the accident: orientation of impact, anthropometry of the victim, front shape of the car. A first simulation has been performed on this starting configuration provided as being the most probable one by the in-depth investigation. Next, effects of some parameters such as car velocity or pedestrian position on impact have been numerically studied in order to find the best correlations with all indications produced by the in-depth analysis. All simulations which were not in accordance with the in-depth investigation were rejected. Finally, the configuration retained is close to the presumed real accident conditions because it reproduces in particular the same impact points on the car, the same injuries, and is according to the driver statement (cf. Serre et al. [14]).

RESULTS

Results Obtained With Simplest Models

Concerning the case No 1 (Xantia) which corresponds to a typical wrap trajectory, analytical and semi-analytical models were applied. Ranges of vehicle impact speeds were calculated for each method considering $D_t \in [16 \text{ m}, 18 \text{ m}]$ and eventual bounds (only given by Searle's method and semi-analytical ones). They are synthesized in table 1. With pa-

Table 1.
Results for case No 1 obtained with simplest methods.

method name	range of vehicle impact speeds V_0 (km/h)
fall and slide	[42,45]
Searle	[42,54]
Rau et al.	[43,57]
Toor and Araszewski	[37,56]
Simms et al.	[42,53]

parameter values $\mu_p = 0.66$ and $H_2 = 1 \text{ m}$, projection efficiency (or impact factor) was set to 1 for "fall and slide" and Searle's models. Regarding Simms et al.'s model, lower bound (respectively upper) so-called probable was chosen with regression parameters: $C = 3.2$, $D = 0.47$, $S_0 = 1.6$ (respectively $C = 3.7$, $D = 0.47$, $S_0 = 1.2$).

Concerning the case No 2 (Twingo) which does not

correspond exactly to a typical wrap trajectory, analytical methods were rejected. Considering $D_t \in [17 \text{ m}, 20 \text{ m}]$ and lower and upper bounds, semi-analytical methods were used in the same conditions as for case No 1. Ranges of vehicle speeds are summarized in table 2. According to driver statement

Table 2.
Results for case No 2 obtained with simplest methods (semi-analytical models).

method name	range of vehicle impact speeds V_0 (km/h)
Rau et al.	[45,60]
Toor and Araszewski	[38,59]
Simms et al.	[44,56]

(time-lag braking) and lack of tire marks on ground, low part of vehicle impact speed range would be selected.

Results Obtained With Wood's SSM

Wood's Single Segment Model assumes that the vehicle decelerates at impact. So it needs a vehicle coefficient friction μ_v to model the interaction between vehicles and pedestrians in terms of primary and secondary segment impacts in vehicle-pedestrian sub-phase. Therefore, Wood's SSM was only used for case No 1. For this case, angle α was varied in the range $[0.20 \text{ rad}, 0.30 \text{ rad}]$ also using different values for impact speed V_0 . Throw distances D_t calculated between 16 m and 18 m allowed us to determine solutions in terms of V_0 . Segment characteristics (location of gravity centre, radius of gyration k) were fixed using the approach recommended by Burg and Rau [1]. In this way, V_0 was determined as belonging to the range $[48 \text{ km/h}, 56 \text{ km/h}]$.

Results Obtained With Multibody Models

Use of the PC-Crash Software

With PC-Crash software, the two cases were treated using its default multibody models. Two pedestrian multibody models are included in the version 6.0 of this software. The one which was used has been validated with dummy crash-tests [9, 10] and seems to give for the two accident cases better results than the other one. The main differences are in the values of the friction coefficients between pedestrian/car and pedestrian/ground both equal to 0.6 for the model we have used and 0.4 and 0.2 for the second one.

Concerning the accident case No 1, the reconstruction results gave an impact speed of 48 km/h for

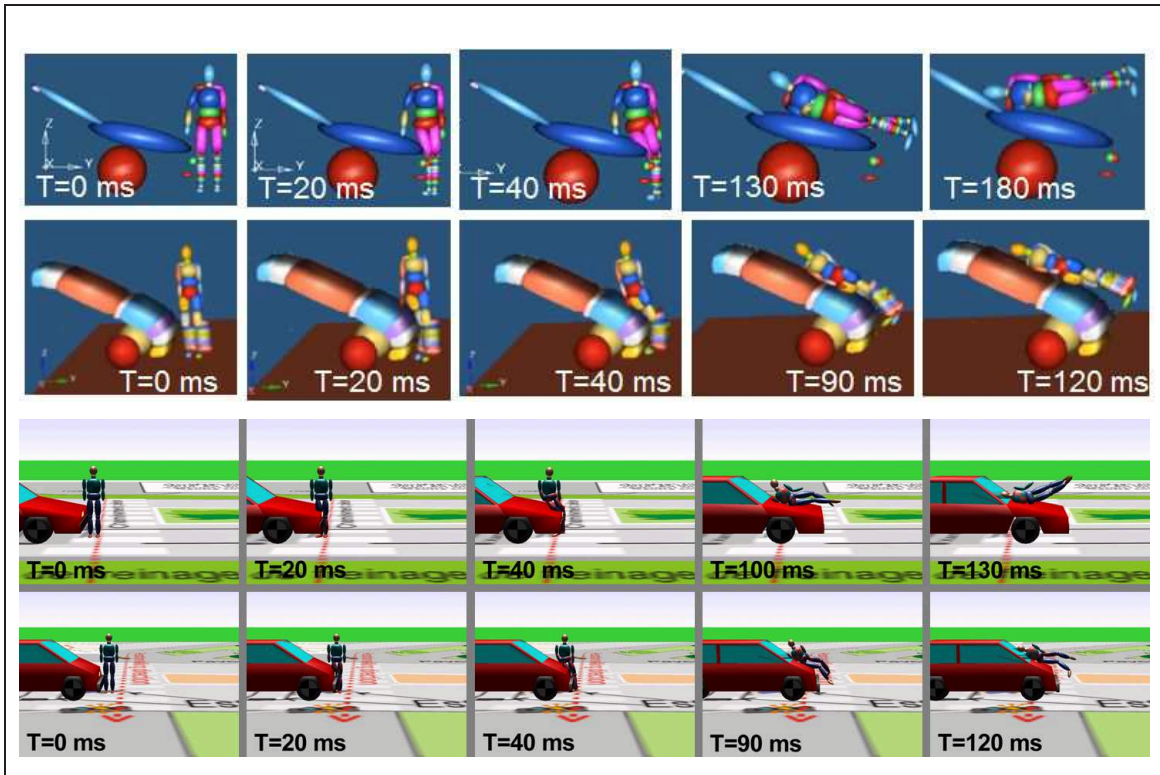


Figure 8. Multibody simulation of the two real accidents with Madymo (line 1: case No 1 (Xantia), line 2: case No 2 (Twingo)) and PC-Crash (line 3: case No 1 (Xantia), line 4: case No 2 (Twingo)).

Table 3.

synthetic table of vehicle impact speed V_0 and pedestrian throw distance D_t obtained (or used) by the different methods for real cases No 1 & 2.

method category	method name	case No 1		case No 2		comments
		V_0 (km/h)	D_t (m)	V_0 (km/h)	D_t (m)	
	in-depth investigation	55	16	[40,45]	19	V_0 evaluated or calculated, D_t measured and evaluated
simple	fall and slide	[42,45]	[16,18]	rejected		D_t input, V_0 output
	Searle	[42,54]	[16,18]	rejected		
	Rau et al.	[43,57]	[16,18]	[45,60]	[17,20]	
	Toor and Araszewski	[37,56]	[16,18]	[38,59]	[17,20]	
	Simms et al.	[42,53]	[16,18]	[44,56]	[17,20]	
advanced	Wood's SSM	[48,56]	[16,18]	rejected		iterative process to determine V_0
complicated	PC-Crash V6.0 pedestrian model	48	16	35	20	
	Madymo V6.0 + specific pedestrian model	50	17	40	18	

the car and a throw distance of 16 m for the pedestrian. The calculated pedestrian final position was quite good for the X axis (in the car way of travelling) but not so good for the Y axis (perpendicular to the car way of travelling) with a difference of 3.5 m with reality. In the simulation, the car stopped 3 m before the real rest position of the car. The calculated pedestrian impact areas on the car were coherent with car deformations (see figures 1 and 8), except for the hip impact which was too high on the car bonnet ($T=40$ ms). However, a relatively important penetration of the pedestrian into the car body ($T=40$ ms, for both cases) was observed showing the difficulty of contact modelling. During the airborne sub-phase, the pedestrian trajectory corresponded to a somersault. Such pedestrian kinematics did not square with the Madymo simulation and neither with PMHS crash-tests for this range of impact speed.

For the accident case No 2, the impact speed of the car is calculated to 35 km/h and the pedestrian throw distance to 20 m. For this case, both final positions, car and pedestrian, were in good coherence with the reality. The simulation provided impact areas on the car coherent with those observed by in-depth investigation. As in the precedent case, the calculated pedestrian trajectory corresponded also to an improbable somersault during the airborne sub-phase.

Use of the Madymo Software

With regard to the more complicated method based on the Madymo software, the accident reconstruction can be decomposed into two phases: the numerical model adaptation and the parametric study. Time consumed to perform both works is about 1 week and numerical simulations last less than 1 hour on a classical PC computer.

Model adaptation concerns the representation of the car, the pedestrian and the definition of an initial accident configuration. Input data are thus a short description of the anthropometry of the pedestrian (height and weight), geometry and mechanical characteristics of the car and an initial impact speed of the car to start the parametric study. This parametric study concerns mainly the velocity of the car, the position of the pedestrian at impact and the pitch angle during the braking phase. Output data concerns qualitative information such as injuries but also quantitative ones such as an accurate impact speed of the car, impact areas of the pedestrian with the car and the throw distance.

Concerning the case No 1 (Xantia), a first simulation was performed on the configuration provided by the in-depth investigation. Car speed was fixed to 55 km/h. Pedestrian was placed in a walking posi-

tion from the left to the right side of the car in order to be impacted on the right side of his body. The configuration retained during the parametric study was the one which reproduced closely the same impact area and the same injuries reported by the in-depth investigation. Four impacts during the simulated kinematic were observed: the lower leg on the bumper, the upper leg on the low bonnet, the shoulder on the high bonnet, the head on the windscreen (see figure 8). Compared to the real injuries, tibia fractures were observed numerically on the third superior part but not on the femur. The retained impact speed for the car was finally 50 km/h and the throwing distance 17 m.

For case No 2 (Twingo), initial car speed was fixed to 45 km/h and the pedestrian position placed in walking posture with the right leg put forwards. After the parametric study, the retained configuration provided a kinematic in accordance with the in-depth accident investigation (see figure 8). Same impact areas were found and fracture on the superior third of the lower leg was simulated. Car speed was finally found equal to 40 km/h and the throw distance close to 18 m.

DISCUSSION

In order to compare the methods in terms of quality of real accident reconstruction, their numerical results corresponding to the case No 1 and No 2 were reported on table 3.

The case No 1 corresponds to a typical wrap trajectory for which skid marks of emergency braking allow us to have a good estimation of the vehicle impact speed (55 km/h). All the methods - except the fall and slide model - provide a solution for vehicle speed on impact compatible or close to the in-depth investigation estimation.

For the case No 2, the vehicle impact speed has been chosen by in-depth investigation as equal to 40-45 km/h. These values have been evaluated from comparison of vehicle damage with those observed on a crash-test (same vehicle, impact speed 32 km/h, PMHS) performed by INRETS-LBA. This case No 2 represents a non typical wrap trajectory (no vehicle deceleration at impact or time-lag after impact) for which the analytical simple and advanced model (e.g. Searle's model) are not suited in term of sub-phase modelling. Therefore, they have not been used contrary to the others methods (semi-analytical simple models and 3D multibody model). From a theoretical point of view, this case highlights limits of the analytical methods (simple and advanced) which didn't take into account enough the contact phase.

Table 4.
Comparative matrix for the different methods.

Complication level	method name	inputs	outputs	precision preconised by author's method	operation bringing time (rough)	computer calculation time	field application
simple	fall and slide [4]	$H_2, D_1 + D_3, \mu_p, PE$	V_0	no element	few minutes	immediate	typical wrap and forward trajectory
simple	Searle [13]	$H_2, D_1 + D_3, \mu_p, PE$	$\min\{V_0\}, \max\{V_0\}$	mathematical lower bound and arbitrary upper ground	few minutes	immediate	typical wrap and forward trajectory
simple	Rau et al. [11]	D_t	V_0	± 5 km/h (corridor)	few minutes	immediate	wrap trajectory
simple	Toor and Araszewski [17]	D_t	V_0	± 7.7 km/h for the 15 th and 85 th percentile prediction interval, ± 12.2 km/h for the 5 th and 95 th one (corridor)	few minutes	immediate	wrap trajectory
simple	Simms et al. [15]	D_t, m_v, m_p , set of regression parameters	$\min\{V_0\}, \max\{V_0\}$	upper and lower bounds depending on degree of certainty (probable, normal, overall)	few minutes	immediate	wrap trajectory
advanced	Wood'SSM [18]	$V_0, m_v, m_p, \alpha, h, dh, bw, k, \mu_p, \mu_v$	V_0, D_t	see statistical models derived from it (e.g. [15])	half an hour	few seconds for one step of the iteration process	typical wrap trajectory
complicated	PC-Crash V6.0 pedestrian model [9, 10]	veh. geometry, m_v , veh. deceleration, V_0 , impact areas, veh. and ped. positions on impact, ped. height, m_p, D_t	V_0 , impact areas, veh. and ped. positions on impact, D_t , 3D kinematics and dynamics	qualitative and quantitative validation based on input/output parameters comparison	one day	few minutes for one step of the iteration process	frontal impact + possible use for other configurations with attention to the validation
complicated	Madymo V6.0 + specific pedestrian model [16, 21, 7]	veh. geometry, m_v , veh. deceleration, V_0 , impact areas, veh. and ped. positions on impact, ped. height, m_p, D_t , injuries	V_0 , impact areas, veh. and ped. positions on impact, D_t , 3D kinematics and dynamics, injuries	qualitative and quantitative validation based on input/output parameters comparison	one week	less than an hour for a step of the iteration process	frontal impact + possible use for other configurations with attention to the validation

Reconstructions performed with PC-Crash and Madymo allow us to compare also kinematics. It has been observed good accordance in the both timing of the vehicle-pedestrian sub-phases (cf. figure 8).

Concerning the comparison of the different methodologies, some criteria have been reported in a general matrix and summarized in table 4. It concerns their requirements (inputs, outputs, computer time, into operation bringing time), their precision (if it is defined by their reference authors) and their field of application (validity domain). Concerning the operation bringing time, it includes, if necessary, the time for measuring specific element such as the vehicle geometry, preparing the adaptation of the pedestrian multibody model, performing the parametric study with the simulation tool, operating results. This general matrix illustrates the relation between the complication increase of mechanical model and the improving of findings related to particular car-pedestrian collisions with a wrap trajectory.

In the first category of methods, analytical and semi-analytical models with simple formalism and very few inputs propose relations (sometimes with lower and upper bounds) between vehicle impact speed and pedestrian throw distance projection. In these relations, the pedestrian position on impact and the vehicle geometry for example are not explicitly used. They rather contribute to the formulation assumptions (e.g. definition of the collision type as a wrap trajectory) which allows us to utilize these simple methods.

In the second category, some more advanced two-dimensional methods like the Wood's SSM try to relate vehicle impact deceleration and speed on impact, throw distance and a few parameters concerning respectively pedestrian and vehicle geometry. The equations obtained in that way are solved iteratively in order to determine an accurate vehicle impact speed. Their assumptions are too simplistic to describe exactly the sub-phase where the pedestrian is in contact with the vehicle. As their equations are moreover difficult to solve, either they are used as a theoretical base for statistical methods (with simpler formalism), or the use of more complicated methods is preferred.

In the third category, the most complicated methods, i.e. the three-dimensional multibody models (used in biomechanics applied to the vehicle passive safety), allows us to relate directly: pedestrian throw distance, vehicle acceleration and velocity during the vehicle-pedestrian contact sub-phase, collision configuration, impact areas on the vehicle

front, pedestrian injuries. Their solution in the context of a real accident reconstruction implies an iterative process which is due to a parametric study. This parametric study has been done for the PC-Crash method only for the car impact speed when it has been done for more variables for the Madymo method: car speed, pitch angle of the car due to braking phase, pedestrian position on impact [14]. Validation of real accident reconstructions performed by these softwares is made mainly with the pedestrian throw distance and the location of the impact points on the car. The Madymo method can allow us to add a validation regarding pedestrian injuries with specific biomechanics models. The application of PC-Crash and Madymo methods in two simple real cases of wrap trajectory highlighted:

- the three-dimensional multibody models are the best-fitted methods to describe the complexity of these collision events,
- they are rather time consuming,
- their accurate and complete utilization is still the appanage of parameterization specialists (in vehicle design, in biomechanics, in medicine, ...) who know about or take part in their experimental validation.

The PC-Crash software uses an important number of parameters to model a pedestrian accident. Most of them are given by default with the software and the results of the accident reconstruction are very sensible to their variations. The apprehension of what they represent of the reality of these complex phenomena is often difficult. Thus the use, apparently "easy", of the PC-Crash software by non specialist users can be dangerous. The PC-Crash technical guideline should be more detailed on the definitions, descriptions, and influences of the numerous parameters needed to compute a reconstruction. The Madymo software method needs also and even more numerous parameters. But because this software is more complicated, its use is reserved to experts in the field of accident analysis and biomechanic.

From a general point of view, the increase in complication of the models corresponds so to the direct use of supplementary material data either as input data (e.g. very detailed geometrical vehicle and pedestrian description) or as validation parameters (e.g. calculated impact areas on the vehicle) which are the simulation results at a step of an iterative process. This approach is particularly pertinent for the in-depth investigation and the forensic field in order to take advantage of the most material

evidence possible by means of hypothetic-deductive models. The adequate use of the multibody models corresponds however to update, multidisciplinary and extensive knowledge with regard to input data (e.g. human body segment inertial parameters) and validity domain of different modellings (e.g. contact modelling between ellipsoids, parts of multibody model).

CONCLUSION

This work was focused on the comparison of different methods allowing real pedestrian accident reconstructions corresponding to a wrap trajectory. This kind of trajectory can be modelled in terms of vehicle impact speed and throw distance with simple formalism models. Methods with different levels of complication were tested with two sets of real data issued from in-depth investigation. They have been classified into three categories: simple, advanced and complicated. For this well-known configuration of vehicle pedestrian collision, the aim was to illustrate in what proportion the increase in complication of a model can improve results in terms of quality. Simple and advanced methods give good results but their validity domain are restrictive (wrap trajectory and forward projection). The increase in complication of the models corresponds to the direct use of supplementary material data either as input data (e.g. very detailed geometrical vehicle and pedestrian description) or as validation parameters (e.g. calculated impact areas on the vehicle). In particular the 3 dimensional multibody models initially developed for passive safety research allow us to relate most of relevant parameters (speed vehicle, impact areas, injuries, ...) of the pedestrian accident. Their applications to the reconstruction are very interesting in the in-depth investigation and forensic fields. It would enable us to achieve reconstruction of other types of collision involving pedestrian (e.g. vehicle frontal impact with fender vault post-impact trajectory, vehicle corner impact), even if there is a lack of material evidence (e.g. no skid mark for an ABS equipped vehicle). That could be possible if the multibody models could be refined and validated for these sorts of real collision configurations. This validation could be based on experimental tests (for example crash-tests using PMHS) reproducing real accident configuration instead of standard ones. Connected to the complementary vehicle primary and passive safety, and the forensic road accident reconstruction, this work would lead to the improvement of the pedestrian safety. It also could be extended to other vulnerable road users such as bicyclists.

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